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Sand source and formation mechanism of riverine sand dunes: a case study in Xiangshui River, China

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Abstract: Riverine sand dunes develop as a result of fluvial-aeolian interactions. The primarily barchan dune chains along the Xiangshui River (a branch of the Xar Moron River in the western part of the Horqin Sandy Land of China) form a typical riverine dune field. We collected a series of samples from the riverine sand dunes parallel to the direction of the prevailing wind and investigated the sand sources and formation mechanisms of these dunes by determining the grain size, heavy mineral content and optically stimulated luminescence (OSL) of the samples. The sand of the near-river dunes was coarser than the sand of the dunes distant from the river, indicating that coarse sand of the valley mainly deposited on near-river dunes. The heavy mineral analysis suggested that wind-sand activity levels were intense on the upwind dunes, but relatively weak on the downwind dunes. This indicated that the sand sources for the near-river dunes were more abundant than those of the distant dunes. Our OSL analysis of samples suggested that the deposition rates on dunes near the river were greater than the deposition rates on dunes distant from the river. The development of dunes along the river indicated that the river played an important role in dune formation and development. In addition, airflow fluctuation and the formation of the waveform dunes had a type of feedback relationship. Grain size, heavy mineral and OSL analyses are widely used methods in wind-sand research. Sand dune grain size characteristics reflect the effects of airflow on the transport and separation of sand materials, as well as the physical characteristics of the sand sources. Heavy mineral characteristics are often used to investigate the relationships between sediments and sand sources. OSL indicates dune age, revealing formation of dunes. Therefore, it is useful to explore dune sand sources, as well as the mechanisms underlying dune formation, by determining grain size, heavy mineral content and OSL. This study investigated the sand sources of riverine dunes and provided new information about riverine dune formation and development.

Keywords: riverine dune; grain size; heavy mineral; optically stimulated luminescence (OSL); Horqin Sandy Land

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1 Introduction

Riverine dunes are primarily in arid and semi-arid regions (Page, 1971; Bullard and Nash, 1998; Bullard and McTainsh, 2003; Ivester and Leigh, 2003; Maroulis et al., 2007; Han et al., 2015).

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China has a large area of arid and semi-arid regions, and riverine dunes are widely distributed in these areas. At present, aeolian dunes have been well studied in China (Liu et al., 1999; Li et al., 2002; Duan et al., 2004; Wang and Zhang, 2005; Wang et al., 2010; Dong et al., 2011), but there have been relatively few studies on riverine dunes although some studies have investigated the sources of riverine dune sand. In the Hotan River Basin, the source of riverine dune sand belongs to the localized type (Qian et al., 1991). The surface material of the Kumtag Desert mainly originates from the Altun Mountains, but the fluvial and lacustrine sediments at the bottom of the Aqik Valley and the lower reaches of Shule River are additional important sources of desert material (Xu et al., 2010). Aeolian sand in the Hulun Buir Sandy Land mainly originates from Hailar; and in Hailar area, terraces and alluvial beach sand are important sources of dune sand (Han et al., 2004). Moreover, riverine dunes on the coastal plains of Georgia (southeastern USA) move continuously eastward, becoming a source of wind-sand, covering all kinds of fluvial landforms in the flood plain (Lvester et al., 2001, 2003).

Some studies have investigated the influence factors about the formation of riverine dunes. A typical type of wind-sand deposition landform is located on the middle and upper reaches of the Yarlung Zangbo River valley on the Qinghai-Tibetan Plateau; and this landform is formed from sediments blown along the valley by the westerly airflow of the upper air (Yang et al., 1984). In the southwest of the Kalahari Desert (Africa), the distribution characteristics of the riverine dunes are closely related to the morphological characteristics of the valley (Bullard and Nash, 1998, 2000). The sediment deposition of estuaries is closely related to the formation of riverine dunes (Lubke et al., 2016). Moreover, rivers play an indispensable role in the development of deserts. In particular, rivers control desert distribution patterns by providing source materials and suitable locations for desert formation and evolution (Yan et al., 2015).

The sand dune belts on the right banks of many rivers in Horqin Sandy Land of northeastern China (including the Xar Moron River, the Xiangshui River and the Laoha River) are nearly perpendicular to the prevailing wind direction, and extend a long distance from the front edge of the river terrace (Han et al., 2015). At present, many of the rivers in the study area have ceased to flow, and thus the fluvial-aeolian interactions of these rivers are not obvious. However, the Xiangshui River continues to flow and has typical riverine dunes. Therefore, the Xiangshui River was selected as the study area to reveal the sand source and formation mechanism of riverine sand dunes.

2 Materials and methods

2.1 Study area

The Xiangshui River, a branch of Xar Moron River (Fig. 1), is located in the western part of the Horqin Sandy Land of China. The Horqin Sandy Land is in a mixed geological region, situated between the complicated Yanshan tectonic belts and the Neocathaysian tectonic system. In this area, quaternary neotectonic movement has had a profound effect, producing thick sand deposits and the thickest sand deposit is 210 m thick. The sediment under the paleosol layer of the original plain is mainly loose fluvial-lacustrine sediment of the Quaternary period. The sediment particles in the study area are 0.01–0.50 mm in diameter, and the sediment is mainly medium-fine sand with high psephicity. During the long process of soil formation, these loose sediments were covered by different thicknesses of sandy chestnut soil. However, sandy chestnut soil has a high sand content and very low resistance, so uncovered ground is easily eroded by wind (Yi et al., 2005). The geomorphological types present in the study area are primarily fixed and semi-fixed dunes, moving dunes, interdunes and flat sandy land.

Xiangshui River runoff is unevenly distributed throughout a year, and the river is intercepted by a dam upstream. Most of the river water originates from rainfall and groundwater. The right bank of the study area has been gradually eroded by fluvial-aeolian interactions, and the angle of the bank has become decreasingly oblique. The Xiangshui River valley is 25–30-m deep and 150–200-m wide. The riverine dunes extend about 2 km from the front edge of river terrace, parallel to the

prevailing wind direction (northwest–southeast). Flat sandy land and sandy meadows are located at downwind. The sand dune field is primarily composed of barchan dune chains, with dune heights of 8–20 m and intredune depths of 5–8 m.

In the study area, the dunes adjacent to the river were relatively high, with patches of brown sand ridge on the windward slope. The brown sand ridges were mostly composed of coarse sand. Sheets of fine sand were also identified on the windward slopes of the dunes, primarily the upper-middle slopes. This indicated that the topographic features of the dune slopes adjacent to the river were complicated, and suggested that the river provided a rich source of sand for the development of adjacent dunes.

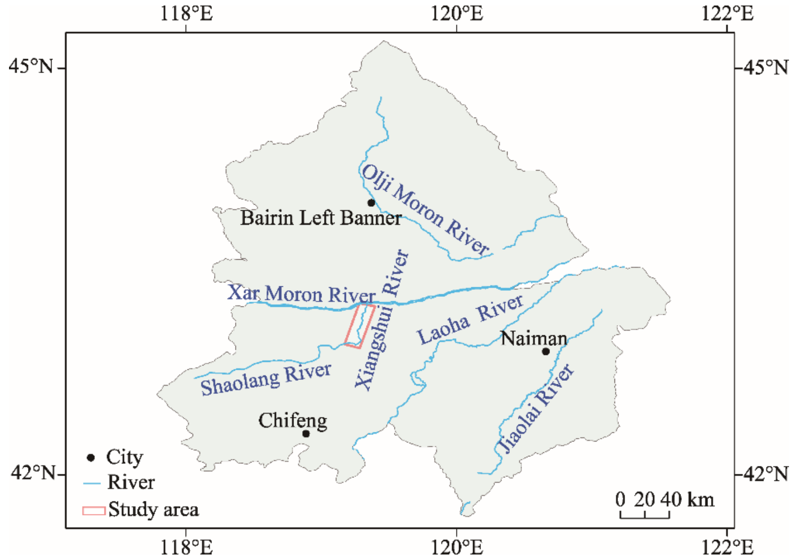

Fig. 1 Location of the study area

2.2 Sampling

To test grain size, we collected 59 sediment samples parallel to the prevailing wind direction (northwest–southeast). Samples were taken from the valley floor, the sand dunes, the interdunes and the flat sandy land (Fig. 2). Three samples were collected from valley floor and seven samples were collected from the surfaces of each sand dune (the windward toe, the lower-middle windward slope, the upper-middle windward slope, the dune summit, the lower-middle leeward slope, the upper-middle leeward slope and the leeward toe). The dunes between the river and the flat sandy

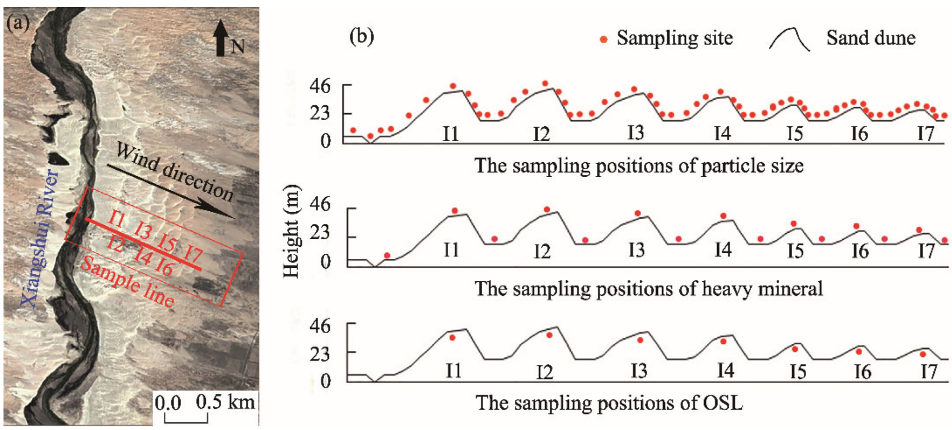

Fig. 2 Locations of sample collection. OSL, optically stimulated luminescence; I1–I7, dunes between the river and the flat sandy.

land were designated I1, I2, I3, I4, I5, I6 and I7. Samples were collected from each interdune (n=6). One sample was collected in the flat sandy land. For the heavy mineral testing, we collected 14 samples from the river floor (n=1), the interdunes (n=6), the flat sandy land (n=1) and the top of each dune (I1–I7; n=7). The samples used for optically stimulated luminescence (OSL) dating were collected from the top of each dune (I1–I7; n=7), at a depth of 1 m.

2.3 Methods

The grain sizes in each sample were determined using a Mastersizer2000 laser grain size analyzer. All of the samples were pretreated prior to testing to remove organic and carboante matters.

The samples for heavy mineral testing were collected from the valley floor, the interdunes, the flat sandy land and the tops of I1–I7. Each 500-g sample was washed in a panning plate to remove mud from the sample surfaces. Then, non-magnetic, electromagnetic and strongly magnetic heavy minerals were separated using the heavy-fluid separation method, the electromagnetic separation method and the strong magnetic separation method, respectively. Finally, we identified the heavy minerals in each sample under a microscope, and recorded the name, color, size, shape, transparency, gloss and abundance of each heavy mineral.

The samples used for OSL dating were collected from the top of each dune at a depth of 1 m. OSL dating was performed by stimulating each sample with light. As the radiation absorbed by the stimulated sample is also released as light, the number of escaped electrons is proportional to the age of the geological sample. Organic matter and calcium carbonate were removed from each sample using 10% HCl and 30% H_2O_2, respectively. Particles 90–150 μm in diameter were extracted by dry sieving. Next, particles with densities of 2.62–2.66 g/cm^3 were selected using two polytungstate heavy liquids, one with a density of 2.62 g/cm^3 and the other with a density of 2.66 g/cm^3. We then added 40% hydrofluoric acid to remove the surfaces of the quartz grains (as these are affected by alpha rays). To remove fluoride precipitation, we soaked each sample for 2–5 days in 35% fluosilicic acid, then added 10% HCl. Finally, we measured the infrared signal and were able to measure the sample when the IRSL (Infrared Stimulated Luminescence)/OSL was less than 10%. The samples were tested using a DA-20-C/DR thermoluminescence/optical luminescence automatic measurement system (Risoe, Denmark) at the Chinese Seismological Bureau. Equivalent sample doses were obtained using the single aliquot regenerative-dose method.

In addition, we analyzed the sand source and formation of riverine sand dunes through the material composition of river terrace (8 m) and artificial profile (14 m) and the remote-sensing images.

3 Results

3.1 Grain size characteristics

The sand in the study area was primarily medium (49.51%) and fine (35.31%) grains (Fig. 3). The dune sand was the coarsest, comprised of 19.64% coarse and very coarse grains. Sand from the flat sandy land was predominantly fine, comprised of 48.36% fine and very fine grains. Valley floor sand was slightly coarser than flat sandy land sand, while interdune sand was coarser than valley floor sand and finer than the sand of sand dune. Thus, although the study area was primarily comprised of medium and fine sand grains, there were some differences in sand grain composition among the different geomorphic forms, possibly because of sand sources difference.

Since sand sources differed, dune sand near the valley was coarser than dune sand distant from the valley (Table 1). That is, I1 (adjacent to the valley) was 49.01% coarse and very coarse grains, and I2 was 24.52% coarse and very coarse grains. Dune sand distant from the valley was finer: samples from I6 and I7 were 37.46% and 34.89% fine grains, respectively. The differences in grain sizes among samples were mainly related to sand source and driving force. The dune sand near the valley was primarily affected by the sand material of the valley slope, while the dune sand distant from the valley was primarily affected by the sand material of the interdunes and by upwind sand flow.

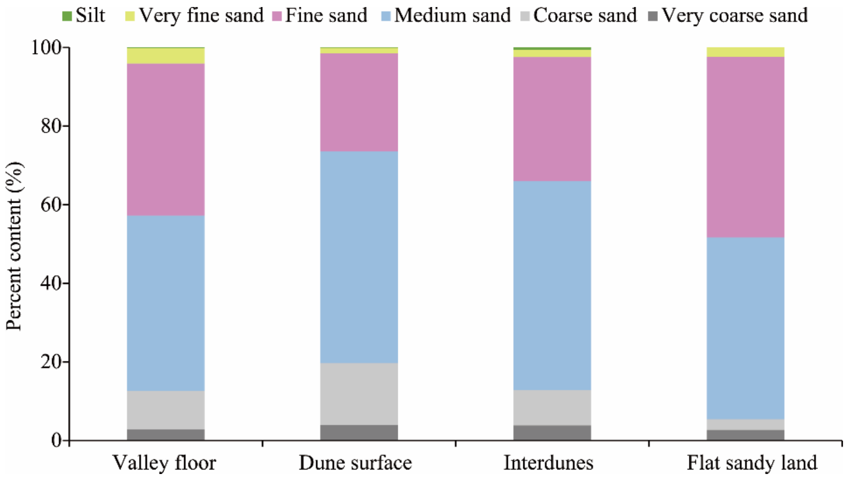

Fig. 3 Grain size composition of the sediment on different landforms

Table 1 Grain size composition of dune sand

Dune	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand
	(%)					
I1	0.00	1.15	4.93	44.90	40.96	8.05
I2	0.00	1.24	17.33	56.91	20.00	4.52
I3	0.00	1.06	24.94	57.15	13.50	3.35
I4	0.00	1.51	25.81	56.62	13.37	2.69
I5	0.10	1.77	29.07	56.12	9.67	3.27
I6	0.00	1.17	37.46	53.60	4.68	3.09
I7	0.15	2.28	34.89	52.36	8.04	2.28

In the grain size frequency distribution curves for the dune sand samples, we observed a double peak for the dune sand near the river (Fig. 4): the first peak was at 1.25–1.75 Φ, and the second peak was at 0.25–0.75 Φ. Dune sand samples distant from the river exhibited a single peak, at 1.50–

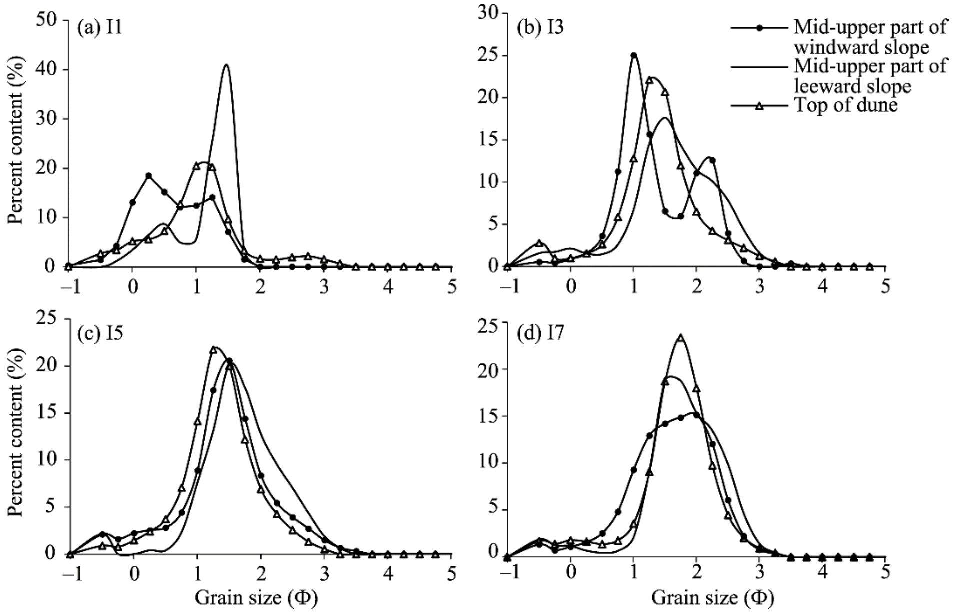

Fig. 4 Grain size distribution curves for deposits from typical dunes

2.00 Φ. From I1 to I7, the grain size distribution curve changed from a double peak to a single peak. In addition, the peak became increasingly narrow. This indicated an alteration in sand source and the influence of wind sorting.

The average grain size of the dune sand near the valley was coarse, while the average grain size of the dune sand distant from the valley was fine (Fig. 5). The mean grain sizes for the samples from I1, I2, I3, I4, I5, I6 and I7 were 0.96, 1.42, 1.60, 1.65, 1.72, 1.86 and 1.83 Φ, respectively. From the windward slope toe to the dune top, the mean grain size for most dunes changed from fine to coarse, but I1 exhibited a reverse trend. This difference was mainly related to sand source. The mean grain size of the dune sand was finest at the lower-middle and upper-middle parts of the leeward slope, and coarsest at the leeward toe. This was primarily due to wind sorting and gravity segregation.

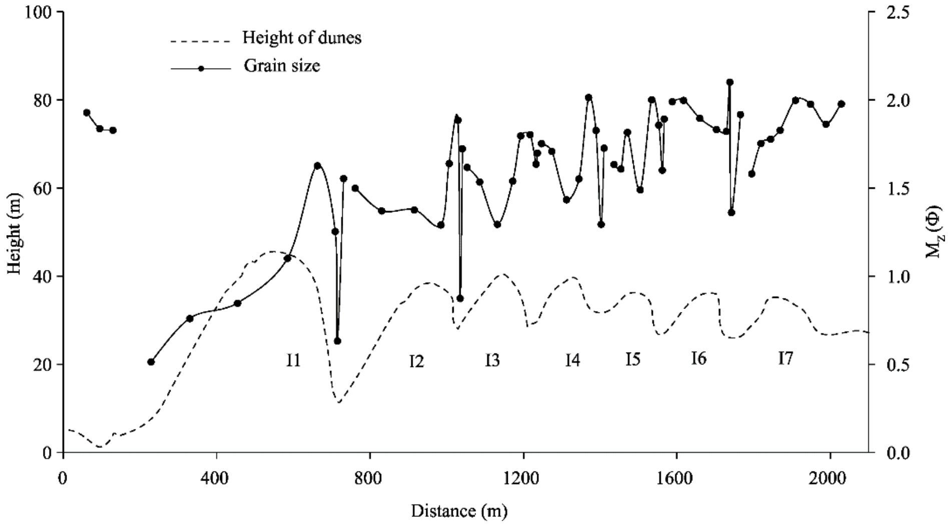

Fig. 5 Variation in mean grain size among riverine dunes

3.2 Heavy mineral characteristics

We identified 20 different heavy minerals across all samples, with hematite/limonite, epidote and garnet the most abundant (44.77%, 22.00% and 15.41%, respectively). All of the other heavy minerals were less than 4.00% abundant. Heavy minerals are divided into very stable, stable, relatively stable and unstable based on how well each mineral resists weathering. Relatively stable and stable minerals were most abundant across all landforms in this study (61.37% and 19.65%, respectively; Fig. 6). Due to environmental influences, stable and very stable minerals were least abundant in the sediment from the valley floor. No other obvious differences in the distribution of mineral stability were detected among the other landforms. However, heavy mineral composition differed between I1 and I7 (Table 2).

Table 2 Characteristics of the heavy minerals in the dune sand

Dune	Very stable mineral	Stable mineral	Relative stable mineral	Unstable mineral
	(%)			
I1	3.16	32.11	55.19	2.21
I2	16.73	25.44	53.38	1.71
I3	8.49	36.78	44.61	3.95
I4	2.44	20.83	68.49	0.27
I5	3.81	10.38	81.51	1.96
I6	2.88	34.94	46.15	6.79
I7	4.33	17.81	67.79	1.16

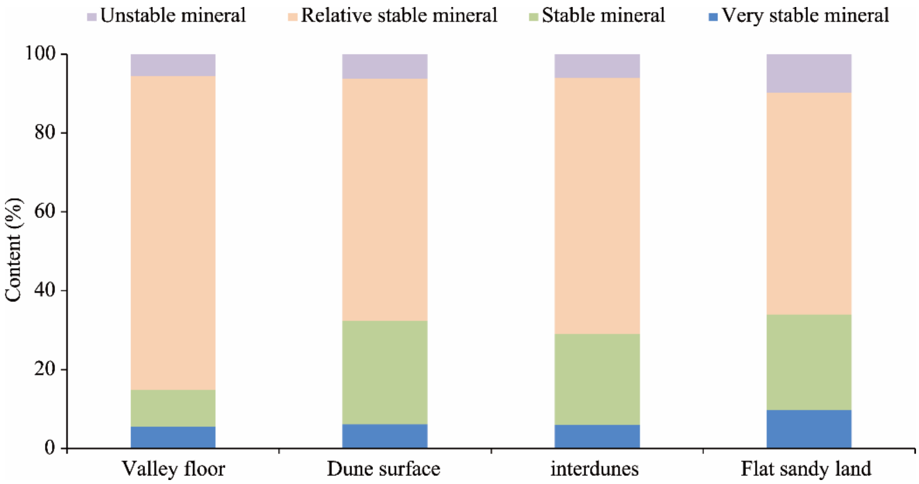

Fig. 6 Heavy mineral characteristics of sediments from different landforms

The ZTR (the mass percentage of extremely stable minerals including zircon, tourmaline and rutile) indices of I1, I2 and I3 were 2.20, 14.69 and 6.29, respectively (Fig. 7). The ZTR index of I1 was lower than those of I2 and I3. In addition, the heavy mineral stability coefficient was greater for I3 (0.93) than for I1 (0.61). The ZTR indices and heavy mineral stability coefficients were similar for I4–I7. The ZTR index values for I4, I5, I6 and I7 were 2.09, 2.72, 2.13 and 2.72, respectively; and heavy mineral stability coefficients for I4, I5, I6 and I7 were 0.34, 0.17, 0.71 and 0.32, respectively. Thus, upwind I1–I3 had high content of stable heavy minerals, high heavy mineral maturity, strong weathering, and intense wind-sand activity. In contrast, stable heavy minerals were less abundant, weathering was weak, and heavy mineral maturity was low for downwind I4–I7.

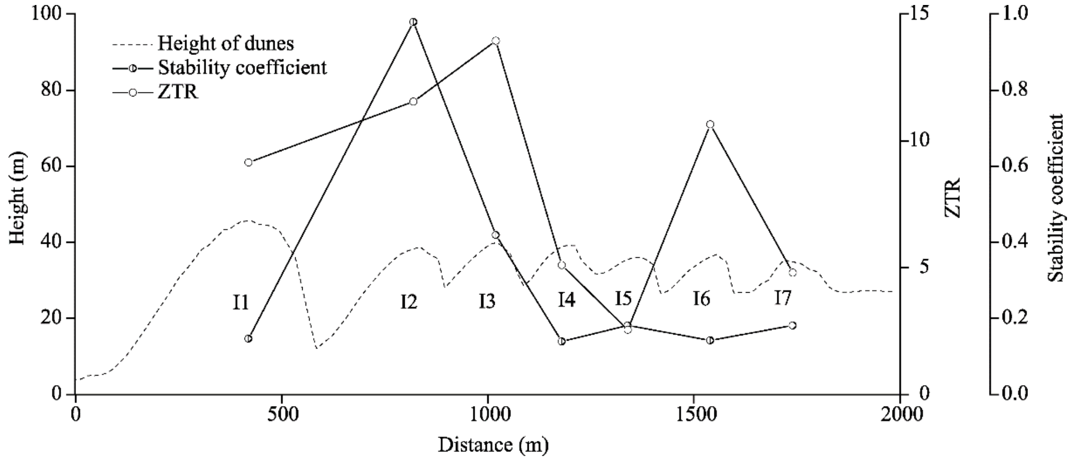

Fig. 7 Heavy mineral parameters of riverine dunes. ZTR, the mass percentage of extremely stable minerals including zircon, tourmaline and rutile.

3.3 OSL dating

OSL samples were taken from 1 m below each dune top (Fig. 8). The OSL results indicated that the sand sample from dune I5 was the oldest (242 a), suggesting that the net deposition rate on this dune was low. In contrast, I2 was the youngest (66 a), suggesting that the net deposition rate on this dune was high. In general, deposition rates were greater on dunes near the valley than on dunes distant from the valley. In addition, the dunes near the valley appeared gray-white in the remote sensing images, representing actively wind-sand activity and suggesting a relatively high deposition rate.

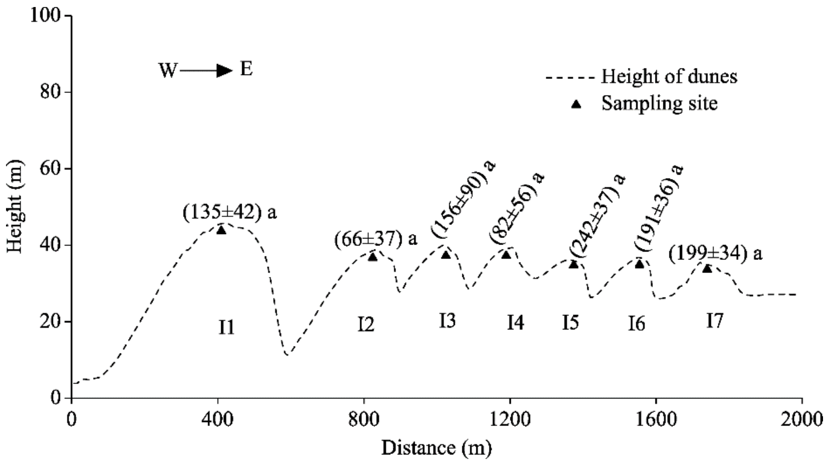

Fig. 8 OSL dating of riverine dunes

4 Discussion

4.1 Comparative analysis of sediments in different areas

Due to variations in sand sources and dynamic conditions, the distribution of grain sizes in the riverine dunes differed from that of dunes in other regions. Indeed, sand in the study area was coarser than those of the Taklimakan Desert, the Badain Jaran Desert, and the Tengger Desert. In the study area, most grains were medium (49.51%) or fine (35.31%). The Taklimakan sand grains were the most fine (extremely fine sand and fine sand, 70%–80%) (Chen and Dong, 1995). Dune sand grains in the Badain Jaran and Tengger deserts were relatively fine, while fine (47.91%) and medium (48.25%) grains were typical of the sand mountains in the southeast of Badain Jaran Desert (Li and Dong, 2011). The dunes at the southeastern margin of the Tengger Desert were more than 60% fine sand (Ha and Wang, 1996). Studies have shown that regional differences in grain size composition are mainly related to sand source, forcing strength and dune age (Ji et al., 1996).

The heavy mineral characteristics in the study area were different from those of other deserts. The heavy mineral stability of the study area was higher than that of the Kumtag Desert or the Junggar Basin. That is, the study area had 63.04% relatively stable minerals, while the Kumtag Desert had 40.5% and 22.5% relatively stable and unstable minerals (Xu and Lu, 2010), and the Jungger Basin had 60.39% and 25.75% relatively stable and unstable minerals (Qian and Wu, 2001). The abundance of extremely stable minerals was greatest in the Badain Jaran Desert, while the abundance of unstable minerals was the greatest in the Tengger Desert (Li, 2011). Thus, heavy mineral composition might vary based on sand source.

4.2 Sand source

The 8-m vertical profile of the river terrace included many coarse sand layers (Fig. 9). Although the 14-m artificial profile, above the river terrace, included fewer coarse sand layers, some coarse sand layers were identified in the lower-middle section of the profile. That is, there were more coarse sand grains in the deep strata and more fine sand grains in the shallow strata. The coarse sand in the near-river dunes primarily originated from the valley slope, while the fine sand in the distant dunes primarily originated from the shallow interdunes and fine sand from the valley via upwind sand flow. Thus, dune sand near the valley was coarser, and dune sand distant from the river was finer.

The high content of stable minerals in I1–I3 indicated that weathering and wind-sand activity were both relatively intense. The high level of wind-sand activity increased the volume of sand deposition on I1–I3, explaining the relatively large size of these dunes. The sand comprising I4–I7 primarily originated from the interdunes and upwind sand flow. The content of stable minerals in I4–I7 was relatively low, and wind-sand activity on these dunes was relatively weak. Thus, the

maturity of heavy minerals in I4–I7 was relatively low, and these dunes were relatively small. The OSL analysis indicated that the sand deposition rate was higher on the near-river dunes than on dunes distant from the river. The higher rate of sand deposition on the near-river dunes indicated that wind-sand activity was more intense on these dunes, as compared to the distant dunes. Thus, the river valley had an important influence on dune development.

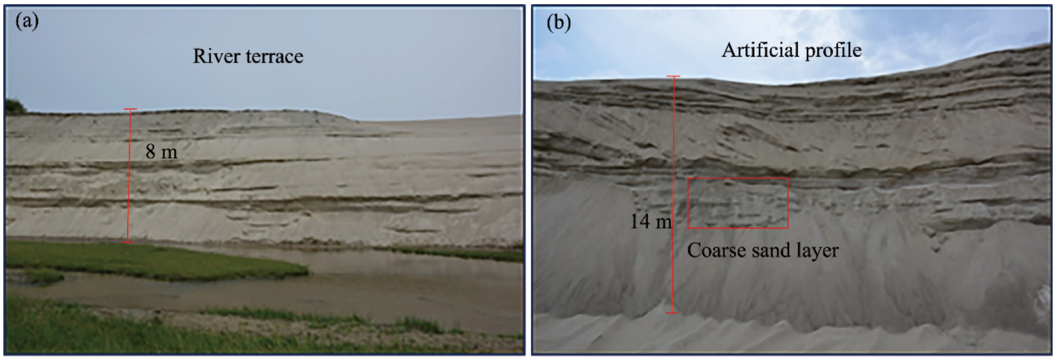

Fig. 9 River terrace and artificial profile of the Xiangshui River

4.3 Mechanisms underlying the formation of riverine dunes

The sand dunes in the study area developed along the river, so it was unsurprising that the river played an important role in the process of sand dune formation (Fig. 10). The presence of a river can disrupt airflow (Sierputowski et al., 1995; Garvey et al., 2005), leading to an airflow acceleration on the upper slope of the riverbank (Wiggs, 1996; Bullard et al., 2000; Bagnold, 2005; Andreotti et al., 2009). The slope of right bank thus became eroded, acting as a sand source for the dunes adjacent to valley. Fluvial erosion also provided sand material for other near-river dunes. The dunes near valley then provided sand material for the downwind areas; this sand deposition destroyed the vegetation in the downwind areas. In addition, airflow over dunes separated and eroded the ground, leading to the formation of interdunes (Kocurek, 1981; Frank and Kocurek, 1996) and providing additional material for the development of downwind dunes. Subsequent dune movements may partially cover the original interdunes, and wind erosion may lead to the development of new interdunes (Allen, 1970; Hunter, 1977; Rubin and Hunter, 1982; Kocurek and

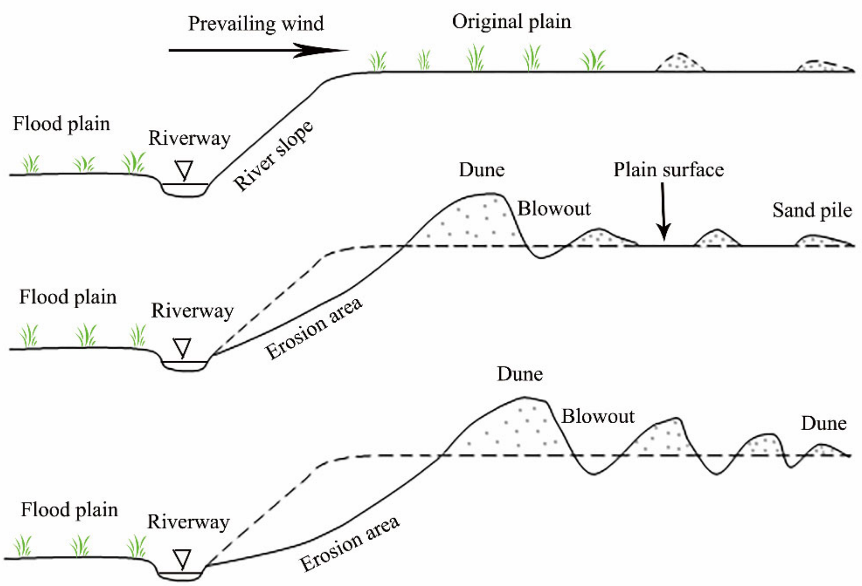

Fig. 10 Formation and development of riverine dunes

Havholm, 1994), further supplying sand material to downwind dunes. Finally, the rising airflow eroded the ground behind the dunes. The dunes and the airflow thus behaved like the waveforms of the sine and cosine functions. The different developmental stages of the dunes at different river locations (Fig. 11) indicated that dune formation was a gradual process (Beveridge et al., 2006), and dunes develop from small to large and from simple to complex.

The OSL analysis also indicated that wind-sand activity near the river was intense, and that the sand deposition rates were higher on the near-river dunes than on the dunes distant from a river. Thus, our results suggested that dune formation and development was not uniform; some dunes developed quickly and others developed more slowly. In addition, the dune development process was dynamically adjusted. As I1 (adjacent to the valley) grew, the height and spacing of the downwind dunes fluctuated, finally resulting in approximately equal-size spaces between the downwind dunes. Thus, the formation and evolution of riverine dunes was not linear, but was instead highly variable. Indeed, the morphological characteristics of the dunes in the study area suggested that, in the absence of large, abnormal disturbances, dunes moved downwind at roughly equivalent speeds, with wave-like dampening. That is, the heights of the downwind dunes decreased gradually.

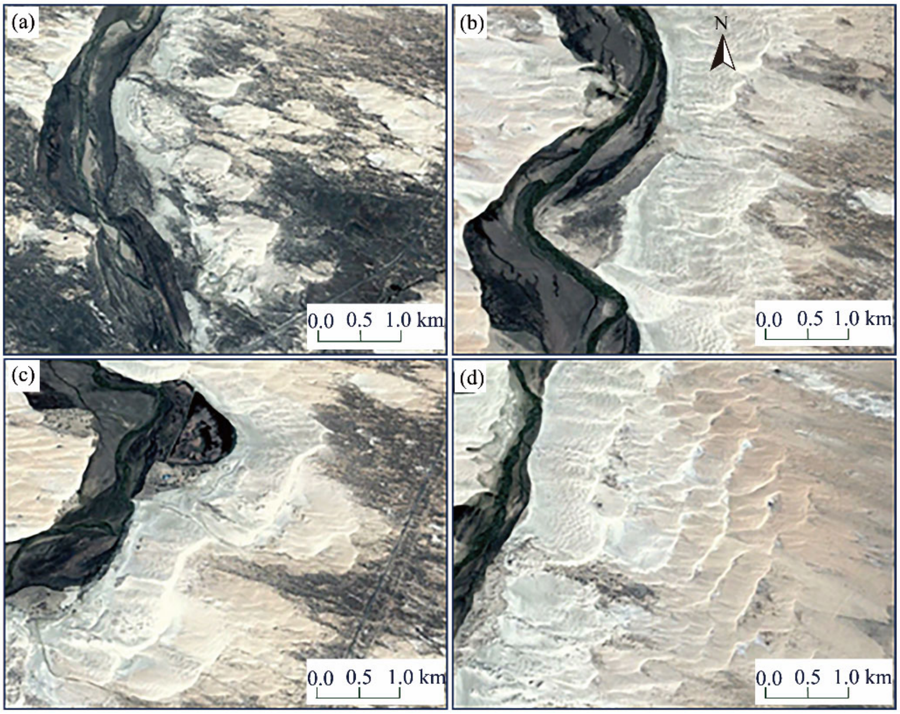

Fig. 11 Riverine dunes at upper reaches (a, c) and middle reaches (b, d) of the Xiangshui River

5 Conclusions

Due to the prevailing winds, the sand dune fields along the Xiangshui River are primarily located on the right bank. Airflow was disturbed by the valley, leading to the formation of the riverine dunes. The right bank of the valley became eroded, providing sand material for riverine dune formation. The fluvial incision was also relatively deep (20–30 m), providing abundant sand material for the dune nearest to the river. Thus, the dune adjacent to the river was relatively high, with a long windward slope. In addition, there were some fine sand sheets and brown sand ridges on the windward slope of this dune. Due to fluvial incision, the coarse sand layers of the deep strata were exposed. Thus, the sand grains from the near-river dunes were relatively coarse.

The development of dunes near the river raised the airflow; airflow split at the summits of these dunes. This led to the erosion of the downwind area, forming interdunes that provided sand material

for the development of downwind dunes. In addition, some of the wind-sand flow from the upwind areas bypassed the dunes, transporting sand material through the sandy beam between dunes. Thus, the near-river dunes were mainly constructed of sand from the slope of the right bank, while the sand source for the distant dunes was primarily the interdunes and the fine sand from valley via upwind sand flow. The sand grains in the study area were coarser than those of other regions, primarily due to riverine downcutting, as this process exposed deeper, coarser sand to the airflow. Similarly, the heavy mineral characteristics of the study area differed from those of other regions. In particular, stable minerals were relatively abundant in the study area. In addition, the heavy mineral and OSL analyses indicated that that wind-sand activity levels on the upwind dunes were high. Thus, more sand was deposited on I1–I3, and these dunes were relatively high. Our results indicated that riverine dune formation is a gradual process, which transitions from simple to complex. The airflow disturbances caused by the presence of the river valley played an important role in the formation of the riverine dunes; airflow fluctuation and the formation of waveform dunes formed a type of feedback loop. Eventually, kinetic energy and the influence of sand sources led to the formation of a series of sine/cosine-waveform dunes.

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